Detection of Warm and Cold Phases of the Neutral ISM in a Damped Lyα Absorber

W.M. Lane, F.H. Briggs

Kapteyn Astronomical Institute, Postbus 800, NL-9700 AV Groningen, The Netherlands.

`wlane@astro.rug.nl, fbriggs@astro.rug.nl`

and

A. Smette[1]

`asmette@band3.gsfc.nasa.gov`

Laboratory for Astronomy and Space Physics, NASA Goddard Space Flight Center, Code 681, Greenbelt, MD 20771.

ABSTRACT

We present a detailed study of the H I 21cm absorption system at $z = 0.0912$ towards the radio quasar B0738+313. The uncommonly narrow main absorption line and weak secondary line are resolved for the first time and have FWHM velocities of $\Delta v_1 = 3.7$ and $\Delta v_2 = 2.2$ km s^{-1} (main and secondary component respectively). In addition we find it necessary to add a third, broader shallow component to obtain a good fit to the spectrum. Although the harmonic mean spin temperature calculated by comparison of the 21cm lines to the damped Lyα line is $< T_s >= 775 \pm 100$ K, the thermal kinetic temperatures of the two narrow components, calculated from their widths, are much lower: $T_k \leq 297 \pm 3$ and $\leq 103 \pm 10$ K respectively. This is the first case of a redshifted absorption system for which T_k is measured to be *less* than $< T_s >$. We discuss this result in the context of a two phase gas model, in which the damped Lyα gas is sensitive to a significant neutral column density of warm phase gas as well as the cold phase gas of the narrow 21cm lines. The third component is interpreted as representing the warm phase gas with with $T_k \leq 5050 \pm 950$ K. The combined column density of the three 21cm components is approximately equal to that derived from fits to the damped Lyα line.

Subject headings: quasars: absorption lines — quasars: individual(B0738+313) — galaxies:ISM

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[1]National Optical Astronomy Observatories, 950 North Cherry Avenue, Tucson, AZ 85726.

1. INTRODUCTION

Damped Lyα (DLA) and H I 21cm absorption lines are the spectral signatures of systems with high neutral hydrogen column densities. Such systems are the major contributors to the mass density of neutral gas at high redshifts ($z \approx 3$). Despite the success of several surveys to identify DLA absorption lines in both the optical (cf. Wolfe et al. 1986; Lanzetta et al. 1991; Wolfe et al. 1995; Storrie-Lombardi et al. 1996) and the UV regimes (cf. Lanzetta, Wolfe, & Turnshek 1995; Rao & Turnshek 1999), our understanding of the morphology and evolution of the host galaxies in which they arise remains poor. Until recently, most of the known DLA systems were at high redshift, making identification and study of the host galaxy difficult.

The profiles of associated metal lines in these systems are consistent with the hypothesis that DLAs arise in rapidly rotating large disks with substantial vertical scale heights (Prochaska & Wolfe 1997, 1998), which fits well with the standard paradigm that DLAs arise in luminous disk galaxies or their progenitors (cf. Wolfe et al. 1995). However, there is a growing body of evidence in both theory and observations that this model might not be applicable to all DLA absorbers. One theory suggests that the interactions of relatively small systems or even proto-galactic clumps might account for the line profiles and neutral column densities of these absorbers (Rauch, Haehnelt, & Steinmetz 1997; Haehnelt, Steinmetz, & Rauch 1998). A number of spectral and imaging studies of low and moderate redshift DLAs have identified a variety of host galaxies with moderate to high luminosities, including compact objects and amorphous LSB galaxies as well as spiral disks (Steidel et al. 1997; Le Brun et al. 1997; Rao & Turnshek 1998).

Just as the morphology of DLA systems is poorly understood, so are their physical conditions, and in particular the temperature of the gas in which the absorption arises. Under usual conditions in the ISM, the excitation, or spin temperature, T_s, describing the hyperfine level populations in the ground state of neutral hydrogen is coupled to its thermal kinetic temperature, T_k. A harmonic mean spin temperature, $< T_s >$, of all of the neutral clouds on a given sightline can be determined by a comparison of H I 21cm absorption and an inferred 21cm emission profile for the same sightline, or by comparison of the 21cm absorption line parameters to a column density from the DLA absorption feature on the same sightline. However the values of $< T_s >$ derived in this manner for redshifted DLA/H I 21cm absorbers are consistently higher than those found in clouds of similar optical depth in the Galaxy (cf. Lane et al. 1998; Carilli et al. 1996).

The two DLA absorption systems identified in the UV spectrum of the $z_{em} = 0.630$ QSO B0738+313 (OI 363), are both examples of low-redshift absorbers with no corresponding luminous disk galaxy (Rao & Turnshek 1998). They are both H I 21cm absorbers, and both have very narrow 21cm lines (Lane et al. 1998; Chengalur & Kanekar 1999). The first absorber is the lowest redshift system for which the DLA line has been observed (note that the "DLA System" at $v \approx 1170$ km s^{-1} reported by Miller, Knezek, & Bregman (1999) was not observed in the Lyman lines, and a measurement of x-ray absorption was used to infer the neutral HI column density). It has a redshift $z_1 = 0.0912$ and a neutral hydrogen column density of $N_{HI} = 1.5 \pm 0.2 \times 10^{21}$ cm^{-2}. It

was discovered serendipitously in a HST-FOS spectrum taken to observe the Ly-α line associated with the previously known metal-line absorption system at $z_2 = 0.2212$ on the same sightline. This second system is also damped, with a slightly lower column density of $N_{HI} = 7.9 \pm 1.4 \times 10^{20}$ cm^{-2}. In ground-based optical images only one candidate host galaxy is visible near the QSO sightline. Based on its optical brightness and the assumption that it is a moderately luminous galaxy, this candidate absorber has been associated with the higher redshift system, although it has no confirming spectroscopic redshift (LeBrun et al. 1993). The other absorption system must arise in either an LSB galaxy or a small galaxy which falls under the PSF of the QSO (Rao & Turnshek 1998).

Here we present new information on the lower redshift ($z_1 = 0.0912$) system on the B0738+313 sightline. Very little is known about the associated metal lines, because the wavelength coverage of the only published optical spectrum (Boissé et al. 1992) does not include the expected wavelengths of any strong lines belonging to this system, while the HST-FOS spectrum (Rao & Turnshek 1998) has insufficient signal to noise and resolution to allow the detection of small equivalent width lines. We present WHT/ISIS[2] observations of CaII H and K, the only metal lines observed so far in this system. We discuss observations of the H I 21cm absorption made with the VLA (Very Large Array)[3], and the Arecibo Radio Telescope[4], and the estimates of temperature which we derive from them. We also present Very Long Baseline Array (VLBA)[5] data which was used to investigate the line characteristics and gas covering factor on parsec, or cloud scales. Because the VLBA achieves subarcsecond resolution, data from these observations provide a fair comparison to the optical data.

2. OBSERVATIONS

2.1. WHT/ISIS

The initial redshift determination of the $z = 0.09$ absorber on the B0738+313 sightline had an unreasonably large uncertainty due largely to the difficulties in fitting damped absorption profiles, and the low signal to noise of the HST detection spectrum. Because an accurate redshift facilitates the search for associated 21cm absorption, observations were made of strong metal lines which fall in the optical window at this redshift. Spectra were obtained using the WHT+ISIS in service mode on the night of 1997 November 9-10, by R. Rutten. The detector was the 2148x4200 EEV10 CCD. We used the R600B grating with a central wavelength of 4300 Å, so that the spectrum covers the

[2]The William Herschel Telescope (WHT) is operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias

[3]operated by The National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

[4]The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under a cooperative agreement with the National Science Foundation

range $\lambda\lambda$ 3420Å– 5200Å. The slit was oriented along the parallactic angle; its width was 1.00" leading to a spectral resolution of $\sim$ 1Å. Two exposures of 900s and one exposure of 1800s were obtained, for a total integration time of 1 hour. The data were reduced with standard MIDAS procedures.

An excerpt of the resulting spectrum is presented in Fig. 1. It shows the Ca II H and K absorption lines with rest equivalent widths of 0.11 ± 0.02 and 0.15 ± 0.02, respectively, at a mean redshift $z = 0.09103 \pm 0.00007$, where the uncertainty represents mainly the RMS of the wavelength calibration. No significant absorption is seen at the expected positions for Fe I λ3720, Al I λ3945, or Ca I λ4227. For completeness, we note that the large peak near 4570 Å is Mg II emission from the QSO (z=0.63), and the region between 4050 and 4320 Å contains a complex of emission lines attributed to Fe II λ2500.

2.2. VLA

The VLA was used in D-array configuration for 4 hours on 1998 January 3 to look for associated H I 21cm absorption at the redshift of the CaII lines. The sources 3C147 and B0735+331 were used to calibrate the amplitude and passband. The observations were made in 2 polarizations, with a bandwidth of 3.125 MHz and 128 channels for a channel separation of 5.6 km/s. The data were reduced using standard routines in AIPS. An unresolved 21cm absorption line was observed at a redshift of $z = 0.09118$, with an optical depth $\tau = 0.08$ and a FWHM velocity $\Delta v = 13.4$ km s^{-1}. By comparing the 21cm line characteristics with the column density from the DLA measurement (see equations in section 5), a harmonic mean spin temperature of $< T_\mathrm{s} > = 775 \pm 100$ K was derived. This temperature represents a column density weighted harmonic mean of the spin temperatures of all of the neutral gas clouds along the sightline. The derived harmonic mean spin temperature is typical of values found in most other redshifted 21cm/DLA absorbers, and is considerably higher than typical values at similar optical depths in the Milky Way (Lane et al. 1998 and references therein).

2.3. VLBA Observations

The $z = 0.0912$ line was observed on 1998 October 8 for just under 6 hours, using the VLBA array, as part of a project that observed both 21cm lines on this QSO sightline simultaneously. All 10 VLBA stations participated in the experiment, but due to technical problems, data from Kitt Peak and Los Alamos were not useful. Pie Town had a clock error which was corrected halfway through the experiment. The compact source B0742+103 was observed for calibration purposes. The data were reduced using standard routines in the AIPS data reduction package. The VLBA system has a poor response at 1163 MHz, so the observations of the $z = 0.2212$ system provided little useful information.

At 1302 MHz the QSO center is lightly resolved into a core and an extended component, as shown in Figure 3, and all of the "core" flux from unresolved observations is recovered. The symmetric, weak, extended lobes, which lie at roughly $30''$ to the north and south of the quasar (Murphy, Brown, & Perley 1993), have been resolved away. Spectra from three locations across the QSO have been extracted. The upper spectrum is offset by one synthesized beam (FWHP) to the north; the lower offset is one beam to the south, and two beams to the east, corresponding to a position along the extension of the QSO. Although nearly 65% of the continuum level in the upper spectrum is due to contaminating signal from the center sightline, the lower position is nearly completely independent and is unlikely to be contaminated at a detectable level. The total shift in position on the sky between the center and lowermost sightline is 13.2 mas, which corresponds to $20 \ h_{75}^{-1}$ pc at the redshift of the absorber.

2.4. Arecibo

The Arecibo Radio Telescope was used to make three one-hour on source integrations of the 1665 and 1667 MHz OH lines in the two absorption systems on the B0738+313 sightline. Given the narrowness of the 21cm absorption features at both redshifts (Lane et al. 1998; Chengalur & Kanekar 1999), we knew that the absorbing clouds must be very cold and therefore might contain detectable molecular gas. The observations were carried out by K. O'Neill on 1998 November 30 and 1998 December 1&3. Using the post-upgrade system, the L-Band wide receiver, and the new autocorrelation spectrometer, it was possible to observe both OH lines at the redshifts of both DLA systems simultaneously by placing 4 bandpass subcorrelators at appropriate frequencies. A bandwidth of 3.125 MHz and 1024 channels gave a velocity resolution of 0.7 km s^{-1} in two polarizations. The observations were made in an on/off "total power" mode. Total power spectra for the calibration source 3C236 were processed to form gain templates for the spectral passbands, and these templates were applied to the B0738+313 difference spectra using Analyz software. The band placed around the OH 1665 MHz line at $z_1 = 0.0912$ was corrupted by interference, and could not be used. No OH was detected in the other three bands (OH 1667 MHz at $z_1 = 0.0912$ and both OH 1667 and 1665 MHz at $z_2 = 0.2212$), which were Hanning smoothed to a velocity resolution of $\delta v = 1.4$ km s^{-1} and had a 3σ detection limit of $\tau = 0.0012$.

On 1999 April 24-25, we observed the 21cm line in the $z_1 = 0.0912$ system for 45 minutes on source using the on/off observation technique, in two polarizations. Placing 2048 channels across the 3.125 MHz bandwidth gave a velocity resolution of 0.35 km s^{-1}. The nearby source J0745+317 was observed as a calibrator. After gain calibration and averaging, a linear baseline was removed from the data using Analyz to produce the spectrum shown in figure 2. Two narrow absorption lines, the principal component observed in the VLA data and the weak secondary component first seen in the GMRT spectrum of Chengular & Kanekar (1999), are clearly resolved and separated from each other in the Arecibo spectrum. In fitting the absorption features we assume that the signal from any 21cm emission in this system is negligible. A sensitive WSRT spectrum (W. Lane,

in preparation) has placed a 3σ upper limit to the H I mass of $M_{HI} \leq 3 \times 10^9$ $M_\odot$ for an assumed velocity spread of 100 km s^{-1} and $H_o = 75$ km s^{-1} Mpc^{-1}. At the velocity resolution of the Arecibo observations, this limit falls well within the spectral noise.

3. COLUMN DENSITY AND TEMPERATURE

The neutral Hydrogen column density in the 21cm line can be calculated using the standard equation:

$$N_{HI} = 1.8 \times 10^{18} \frac{T_s}{f} EW_{21} \text{ cm}^{-2} \tag{1}$$

where f is the fraction of the continuum source covered by the absorber, T_s is the spin temperature of the gas, and EW_{21} is the integral of the optical depth over the velocity range of the line in units of km s^{-1}. For a single line with a Gaussian profile, $\tau(v)$,

$$EW_{21} = 1.06 \times \tau_c \, \Delta v \tag{2}$$

where τ_c is the peak optical depth of the line at the line center and Δv is the FWHM velocity in km s^{-1}.

The covering factor f of the gas in 21cm absorbers is usually assumed to be $f \equiv 1$ for compact QSOs, based on a variety of arguments (cf. Carilli et al. 1996). VLBI measurements can be used to refine estimates for f for more complex sources (Briggs & Wolfe 1983). Adoption of a value for f allows a calculation of either the column density, if the temperature is known, or of the temperature if the neutral column density is known from a DLA measurement. B0738+313 is a core dominated quasar, with only $\sim 2\%$ of its total flux found in weak lobes which extend $\approx 30''$ north and south of the core at this frequency (W. Lane, in preparation; Murphy et al. 1993). New WSRT observations (W. Lane, in preparation) find no evidence for the presence of the main component line against the extended lobes, and any other absorption is ruled out at 3σ optical depths of $\tau_{north} \approx 0.03$ and $\tau_{south} \approx 0.08$, for velocity resolution $\delta v = 4.5$ km s^{-1}) over velocities in a range of several hundred km s^{-1} to either side of the main component redshift. This implies that the covering factor of the absorbing gas is $f \leq 0.98$ over the entire QSO.

Within the errors, the width, depth and redshift of the main absorption line do not change across the core of the quasar in the VLBA data. The size scale and low velocity dispersion of the gas causing the main absorption feature suggest that it belongs to a single cold cloud or cloud complex. More sensitive VLBA measurements would be necessary to determine if the weak secondary absorption is also present over this size scale, or is part of a smaller scale feature. The constancy of the primary line characteristics over the slightly resolved core in the VLBA data suggests that it is completely covered ($f_{core} = 1$) by the absorbing gas in that component, and we assume this is true for the second weaker component as well. We therefore adopt the view that the absorbing gas entirely covers the core but not the extended weak lobes, and that the covering factor of the gas is $f \approx 0.98$.

The extreme narrowness of the absorption features (as measured in the Arecibo data) places firm upper limits on the amount of thermal broadening in the lines, and consequently on any turbulence or bulk motions of the absorbing gas. As a result, an upper limit to the kinetic temperature for each cloud can be found directly from the widths of the lines, without having to rely on a comparison between the DLA and 21cm line characteristics to calculate a harmonic mean spin temperature for the entire ensemble of clouds which lie on the sightline. The kinetic temperature of the gas is related to the width of the absorption line by:

$$T_{\rm k} \leq \frac{1.2119 \times 10^2 \Delta v^2}{8 \ln 2} \ \ {\rm K} \tag{3}$$

where Δv is the FWHM velocity measured in km s^{-1}.

4. WARM PHASE GAS

A simultaneous two component fit to the Arecibo spectrum left large residuals and had a reduced $\chi^2 = 2.34$. By adding a third component to the fit, the reduced $\chi^2 = 1.02$, and the residuals were all within the noise. The first or main component has a velocity width at half maximum (FWHM) of $\Delta v = 3.687 \pm 0.019$ km s^{-1}, and an optical depth of $\tau = 0.2462 \pm 0.0010$. It lies at a heliocentric frequency of 1301.6496 MHz, corresponding to $z = 0.09123$. The second, weaker line is separated from the first by $\Delta V_{\rm offset} = 7.69 \pm 0.04$ km s^{-1}. It has a FWHM velocity of $\Delta v = 2.18 \pm 0.11$ km s^{-1} and an optical depth $\tau = 0.0253 \pm 0.0010$. The third component has an optical depth $\tau = 0.0063 \pm 0.0008$ and FWHM velocity $\Delta v = 15.2 \pm 1.4$ km s^{-1}. The absorption is shifted by $\Delta V_{\rm offset} = -1.59 \pm 0.66$ km s^{-1} with respect to the main narrow absorption feature. Attempts to force the third component to lie at the position of either of the other two components resulted in much poorer fits. Figure 4 shows the Arecibo spectrum after the fits to the first two components have been removed. The fit to the third component has been marked, and the residuals after removing all three gaussian fits are shown. Parameters for each of the absorption components are summarized in Table 1.

Using equation (3), the kinetic temperature is $T_{\rm k} \leq 297 \pm 3$ K for the main component and $T_{\rm k} \leq 103 \pm 10$ K for the secondary line. Both of these temperatures would fall within the scatter in the Galactic relation for $<T_{\rm s}>$-τ (Braun & Walterbos 1992), unlike the considerably higher temperature $<T_{\rm s}> = 775 \pm 100$ K that was derived earlier. This is the first redshifted system for which it can be shown that $T_{\rm k}$ is less than $<T_{\rm s}>$, ie. that the kinetic temperature in the individual cold phase gas clouds is less than the derived harmonic mean spin temperature for all of the neutral gas on the sightline. The kinetic temperature of the third line, derived from the velocity width of the line, is $T_{\rm k} \leq 5046 \pm 953$ K, in reasonable agreement with measurements of temperature in the WNM of our own Galaxy (Kulkarni & Heiles 1988; Carilli, Dwarakanath & Goss 1998), where typical temperatures fall in the range 5000-8000 K.

For a given cloud, $T_{\rm s} \approx T_{\rm k}$ under usual conditions found in the ISM (Kulkarni & Heiles 1988).

For the two cold absorption components, we set $T_s = T_k$ and $f = 0.98$ (because the Arecibo beam covers both the core and the extended lobes of the quasar), and calculate the column density for each 21cm line component from equations (1) and (2). Adding the two together, and bearing in mind that our values for T_k are upper limits, we find a total column of $N_{HI21cm} \leq 5.4 \pm 0.1 \times 10^{20}$ cm^{-2} in the narrow absorption features. This is approximately one third of the measured H I column density in the DLA line: $N_{HIDLA} = 1.5 \pm 0.2 \times 10^{21}$ cm^{-2} (Rao & Turnshek, 1998).

The calculated column density in the warm component is $N_{HI} \leq 9.4 \pm 2.3 \times 10^{20}$ cm^{-2} for a covering factor of $f = 0.98$. Although we do not have the needed sensitivity to determine the core covering factor for this component in the VLBA data, warm gas in our Galaxy is distributed more widely and more uniformly than the cold gas (Dickey & Lockman 1990), so it seems unlikely that the gas would have a lower core covering factor than the cold gas. There is the possibility that the warm gas covers one or both of the weak extended radio lobes as well as the core (ie. that $f > 0.98$), but given that $30'' \approx 45h_{75}^{-1}$ kpc at $z_1 = 0.0912$, it seems unlikely. The absorption limits against the extended lobes (W. Lane, in preparation) and the EW_{21} of the warm absorption in the Arecibo spectrum rule out the possibility that the absorption covers one of the lobes but not the core as well.

When the warm and cold component column densities are added together, the total column density in 21cm absorption on this sightline is $N_{HI21cm} \leq 1.48 \pm 0.24 \times 10^{21}$ cm^{-2}. This is in remarkable agreement with the column density from the fit to the DLA line.

5. DISCUSSION

The existence of a second gas phase has often been suggested to explain the large harmonic mean spin temperature values, typically $< T_s > \approx 1000$ K (cf. Carilli et al. 1996) found in redshifted DLA/21cm absorbers. If the gas on the sightline has two (or more) temperature phases, then the T_s calculated by comparing the 21cm and DLA absorption profiles will not be equal to the kinetic temperature in either phase, but rather to a column-density weighted harmonic mean of the temperature of each phase. Thus a sightline with mostly warm phase gas will have a higher calculated $< T_s >$ than one with mostly or only cold phase gas. The values found for $< T_s >$ can then best be interpreted as an upper limit to the temperature of the cold phase gas. When this quantity is derived for redshifted systems, it is usually a value somewhere between the measured temperatures of stable cold and stable warm neutral gas in our own Galaxy. In most redshifted 21 cm absorbers, the absorption lines are broadened by bulk kinematic motions of the gas, and the limit on the kinetic temperature is higher than that of the $< T_s >$.

This is the first redshifted 21cm absorber measured for which the calculated thermal T_k which constrains the cold gas temperature more tightly than the derived $< T_s >$, and shows directly that not all of the gas column density seen in the DLA line appears in the cold components of the 21cm line, as we expect from the value of $< T_s >$. It suggests that some two-thirds of the

column density on this sightline, if not more, is contained in warm phase gas. If the broad shallow component we have detected in our Arecibo data were to be resolved by more sensitive observations into a collection of shallow narrow absorptions lines, then the conclusion that warm phase gas is necessary to explain all of the DLA fitted neutral column density in this system would still remain. The integrated $N_{\rm HI}$ in such an ensemble of little narrow cold components would be very small, and we would still need to find the rest of the gas sensed by the DLA observation. The logical place for it to be "hiding" from the 21cm absorption measurement would still be in a warm neutral component, appearing as an even broader and shallower absorption feature.

This system offers an explanation for why some DLA absorbers which fall in front of radio-bright QSOs do not show 21cm absorption. There is $N_{\rm HI} \approx 10^{21}$ cm^{-2} column of gas which was "unseen" in the 21cm spectrum until extremely sensitive observations were made. This amount is well over the canonical lower limit for DLA systems, and its existence here suggests that some fraction of the DLA systems may arise in entirely warm phase gas. This idea is strengthened by the lower limits found on $< T_{\rm s} >$ for 21cm non-detections, which are typically several times 10^3 K, suggestive of either unstable or warm phase gas (WNM) (Carilli et al. 1996). Given that the WNM is more widely and uniformly distributed than the CNM in our own Galaxy (cf. Dickey & Lockman 1990) and in observations of local Dwarfs (Young & Lo 1996,1997), it seems likely that the gas responsible for any detection of DLA absorption would include a large fraction of warm phase neutral gas.

In conclusion, we are able to derive not only a harmonic mean spin temperature for the B0738+313 system, but also a thermal kinetic temperature for the gas in the narrow-line absorbing clouds. For the first time in a redshifted H I 21cm absorber, the kinetic temperature derived from the velocity width of the absorption is observed to be smaller than the derived spin temperature. The neutral gas must be split into warm and cold phases in order to account for this discrepancy. We find that the 21cm absorption spectrum is best fit by three components; two narrow deep lines, assumed to arise in cold gas with $T_{\rm k} \leq 300$ & 105 K, and a broad shallow absorption feature which we identify with the warm phase gas at $T_{\rm k} \leq 5050$ K. Within the errors, all of the neutral hydrogen column density seen in the DLA measurement is recovered by these three 21cm absorption components. This is the first detection of warm phase gas in absorption in an extragalactic system, and the highest redshift detection of warm neutral phase gas known. It is also the first time limits on temperature have been made in a redshifted DLA system which show a two temperature distribution of the neutral gas, comparable to that found in our own Galaxy.

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Table 1: Three Component Fit to the 21cm Absorption

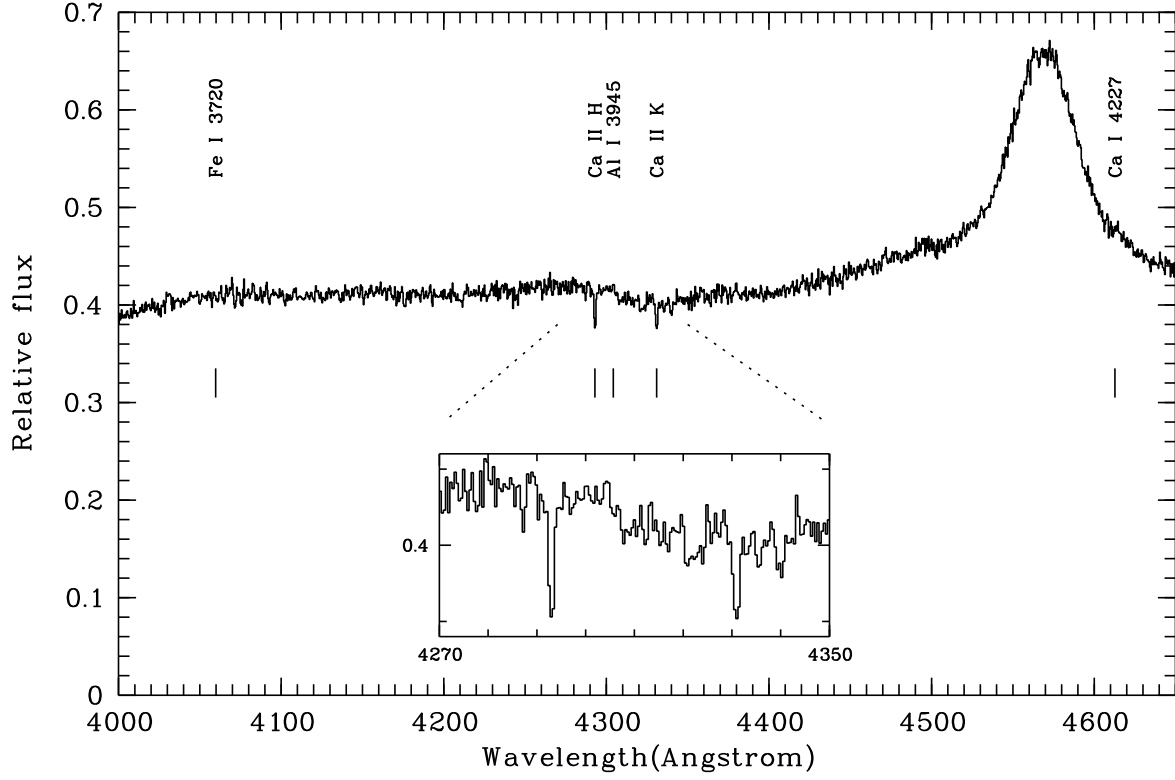| Component:	1	2	3
Optical depth:	0.2462±0.0010	0.02527±0.0010	0.0063±0.0008
Δ V_{offset}(km s^{-1})		7.69±0.04	-1.59±0.66
FWHM(km s^{-1})	3.687±0.019	2.18±0.11	15.2±1.4
T_k(K)	297±3	103±10	5046±953
$N_{HI}(10^{20}$ cm^{-2})	5.27 ± 0.02	0.11 ± 0.01	9.4 ± 2.3

Fig. 1.— WHT/ISIS spectrum of Q0738+313. Ca II H and K absorption features at a redshift of $z = 0.0910$ are marked. No significant absorption is seen at the expected positions for Fe I $\lambda3270$, Al I $\lambda3945$, or Ca I $\lambda4227$.
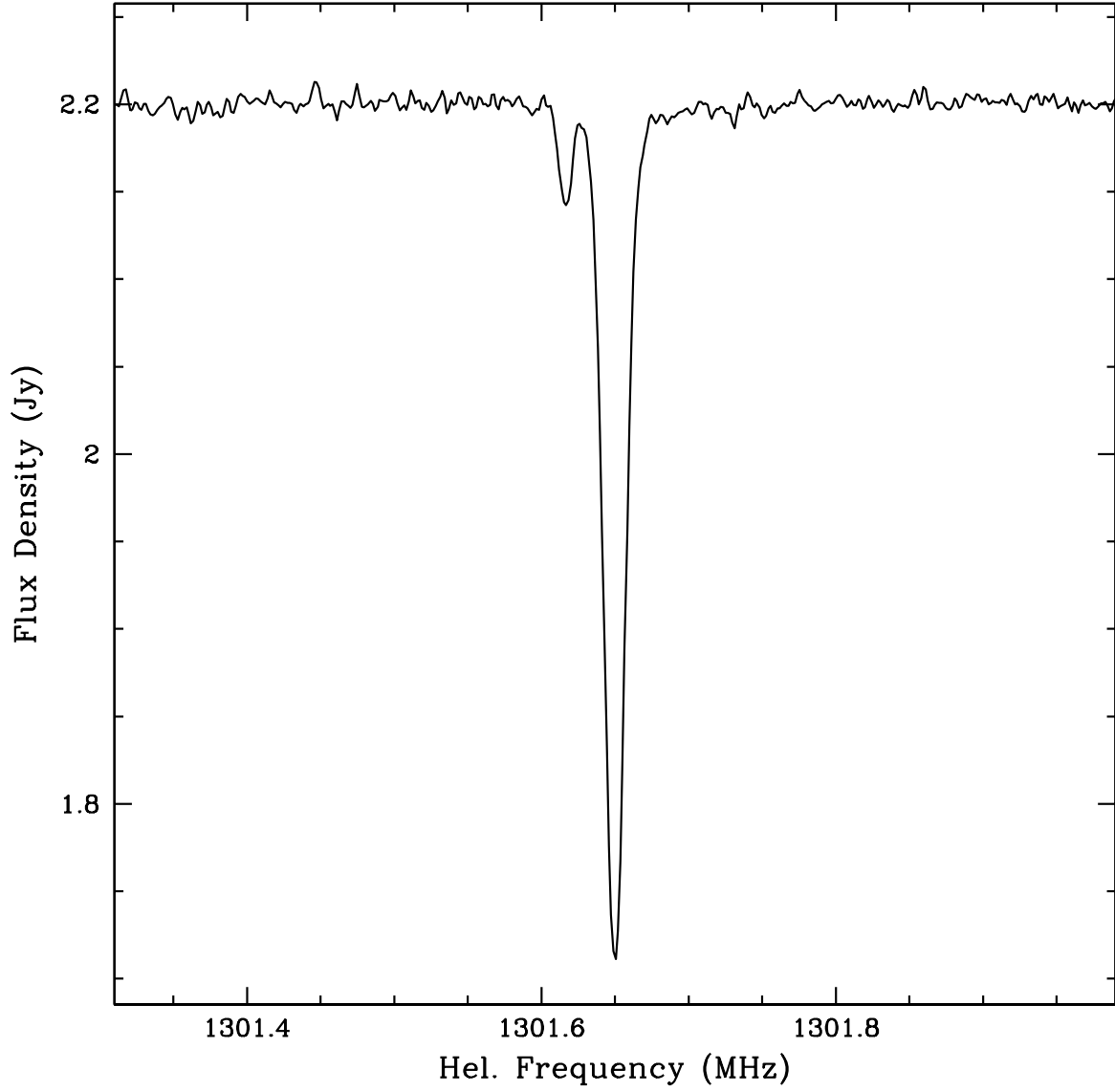
Fig. 2.— Arecibo observations of the H I 21cm line at $z = 0.0912$ towards the QSO B0738+313. Channel spacing is 0.35 km s^{-1}, allowing this extremely narrow line to be resolved for the first time, and showing the second component clearly separated from the main component.
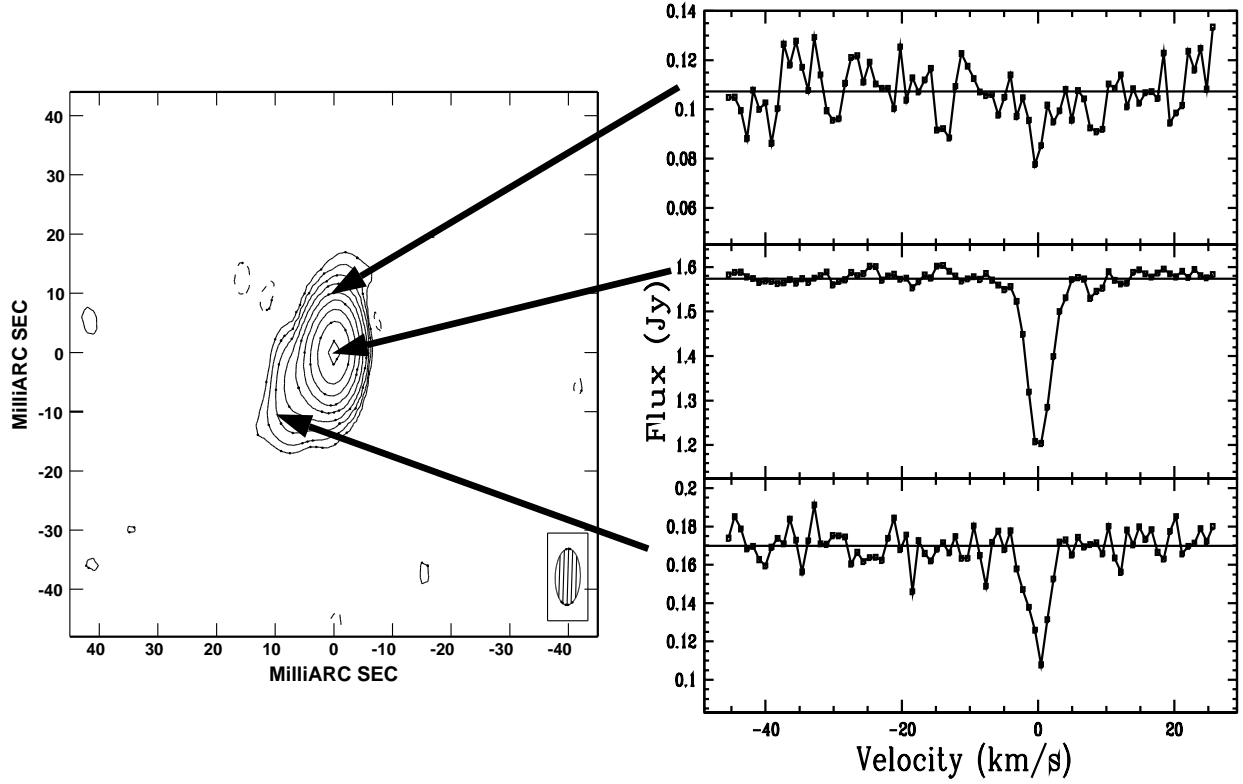
Fig. 3.— Contour plot of the core of B0738+313 observed with the VLBA at 1302 MHz. The quasar is lightly resolved showing a slight extension to the southeast. Spectra have been extracted at the three positions indicated by the arrows. The top spectrum is at $\delta x = 0, \delta y = 10$ mas, the center is at $\delta x = 0, \delta y = 0$, and the bottom at $\delta x = -10$ mas, $\delta y = -10$ mas. At a redshift of $z = 0.0912$, 10 mas corresponds to 15 h_{75}^{-1} pc. The synthesized beam (FWHP) is roughly 5 mas by 10 mas. The velocity scale is centered with $v = 0$ at a heliocentric frequency of 1301.65 MHz.
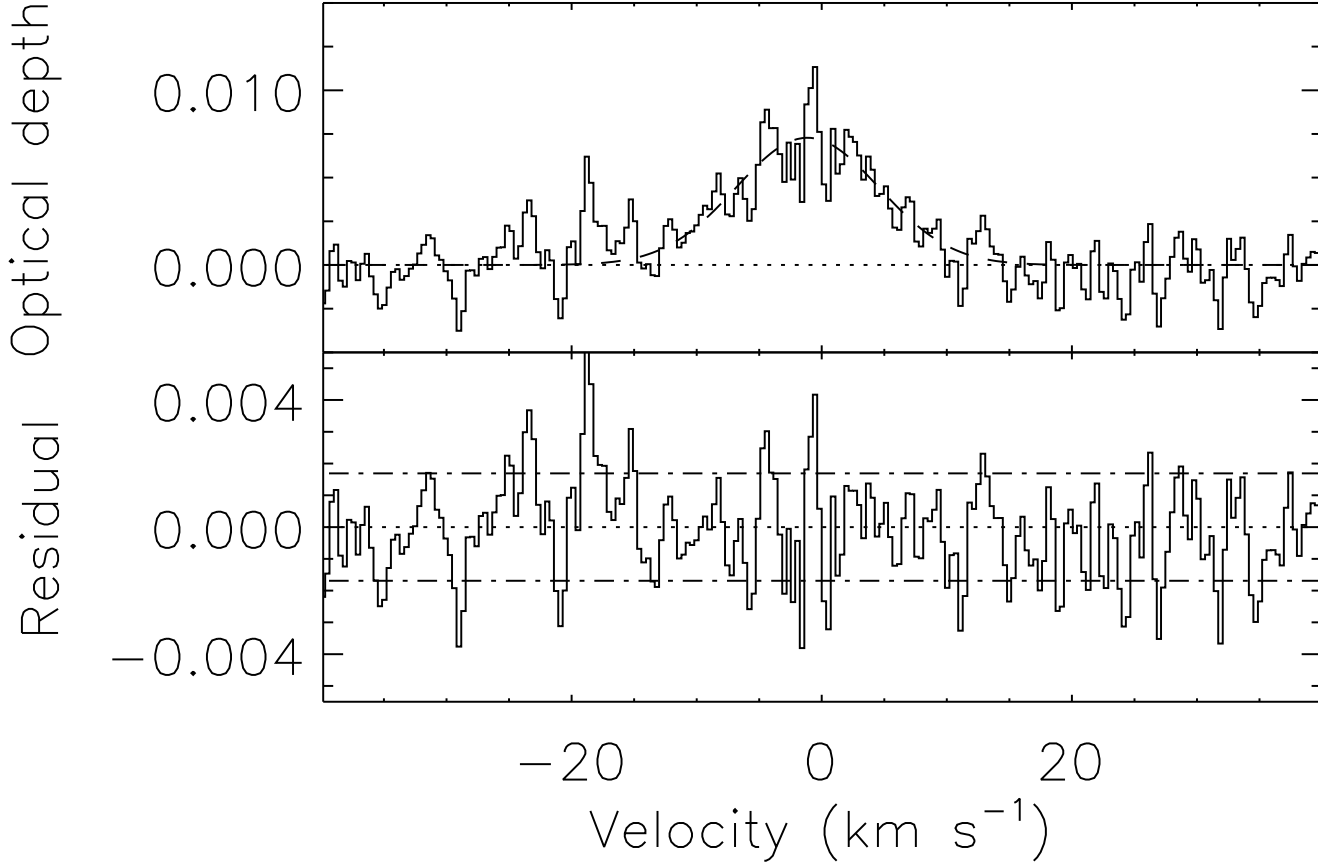
Fig. 4.— Arecibo spectrum showing the warm component and its fit. The velocity scale is set so that $v = 0$ corresponds to a redshift of $z_1 = 0.09123$. The upper panel shows the spectrum after the Gaussian fits to the two cold component absorption lines have been subtracted. The third warm component is clearly visible, and a dashed line shows the gaussian fit to it simultaneously with the two cold components. The lower panel shows the residuals after subtracting all 3 components, with 1σ error levels marked by the dash-dot lines.